



**National
Transportation
Safety Board**

Airplane Lift and Stall, Ground Effect, and Takeoff Speeds

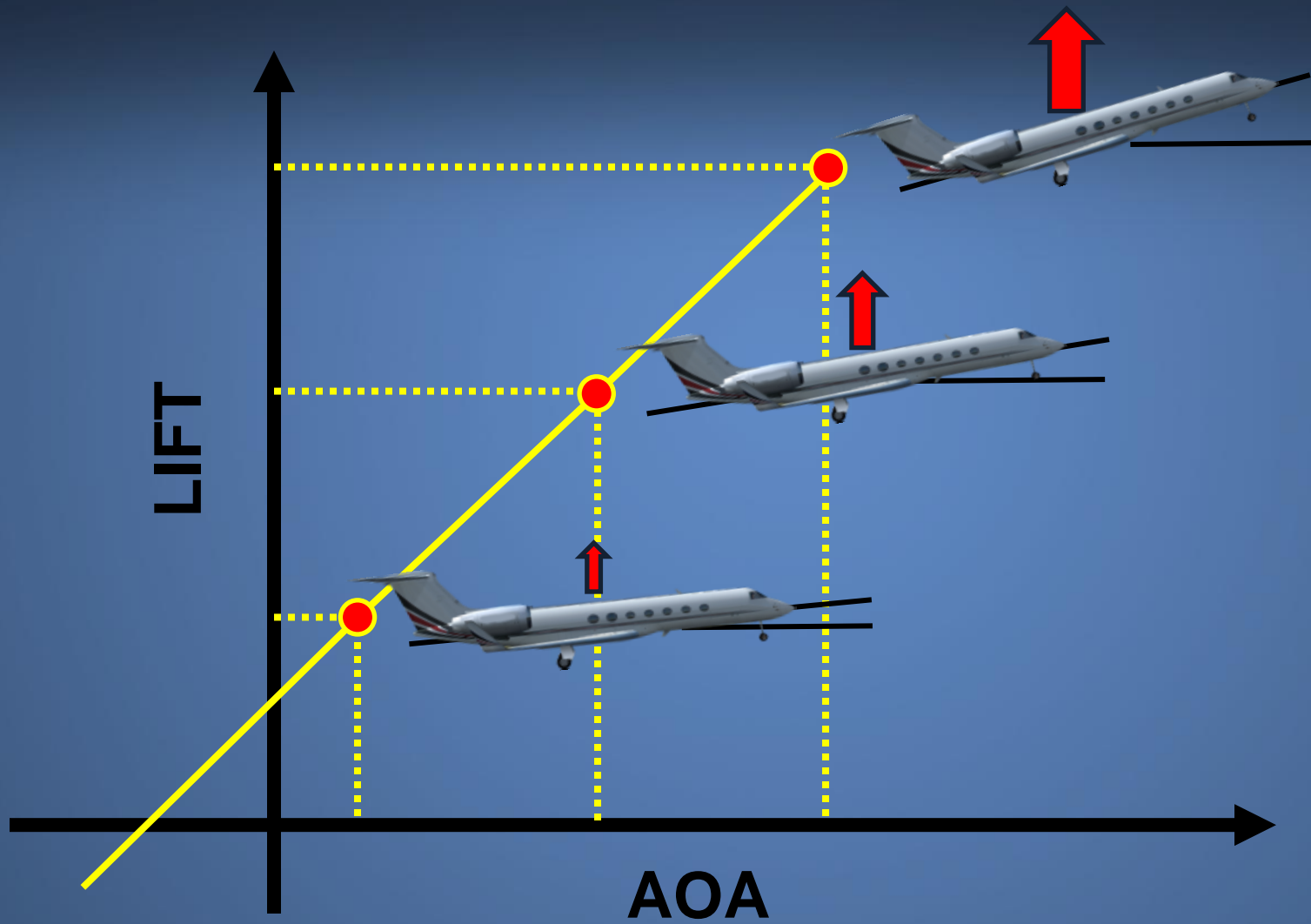
Aircraft Performance presentation

Airplane Lift and Stall

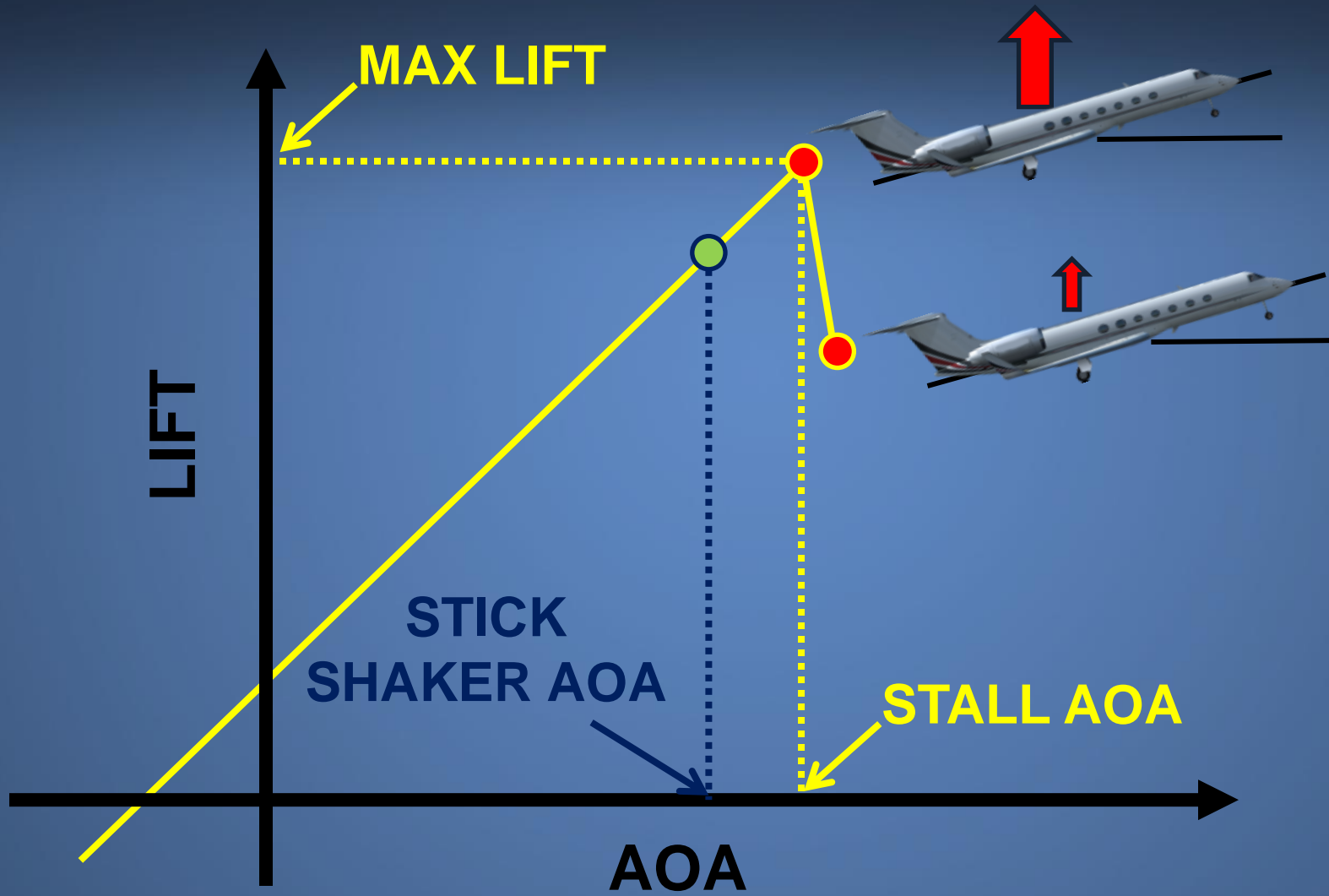


Lift is proportional to $AOA * (airspeed)^2$

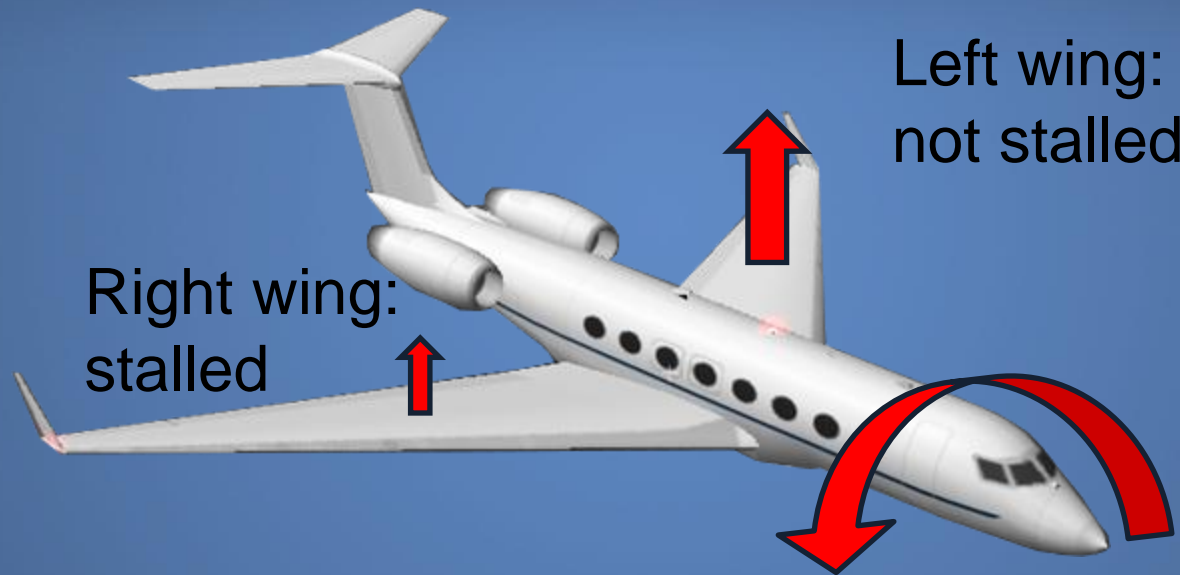
Airplane Lift and Stall



Airplane Lift and Stall

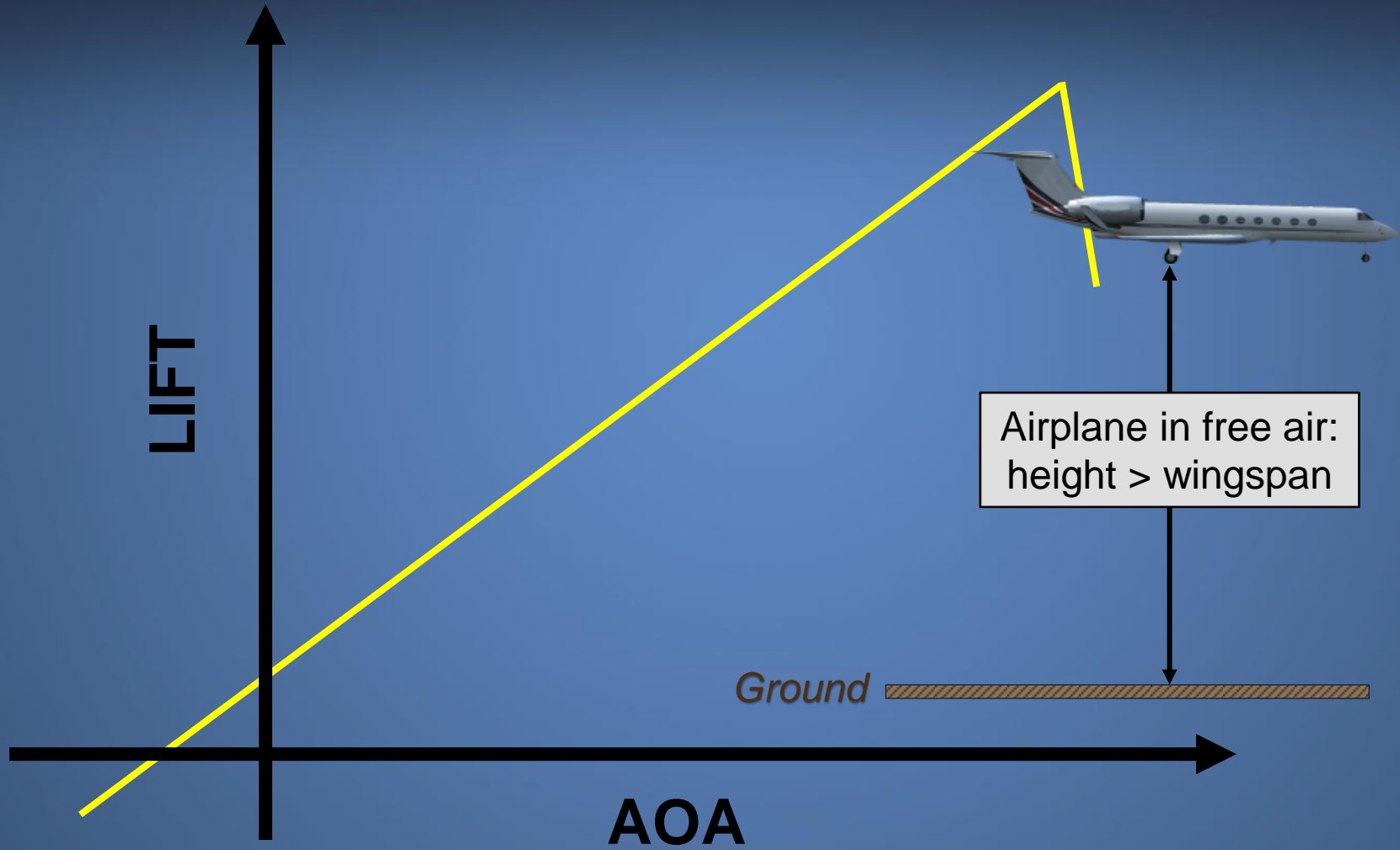


Rolling Moment Due to Asymmetric Stall

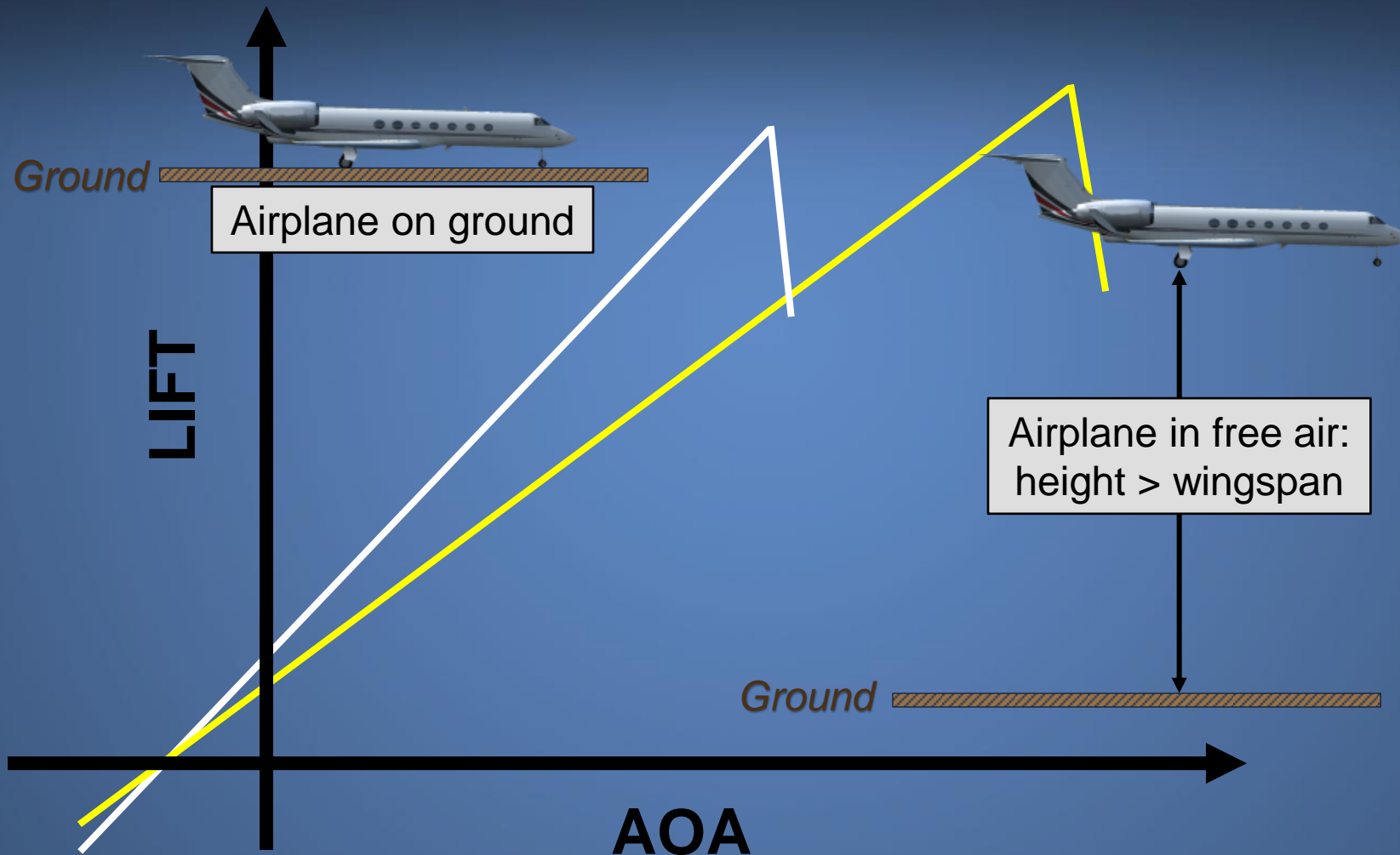


Result: rolling moment to the right

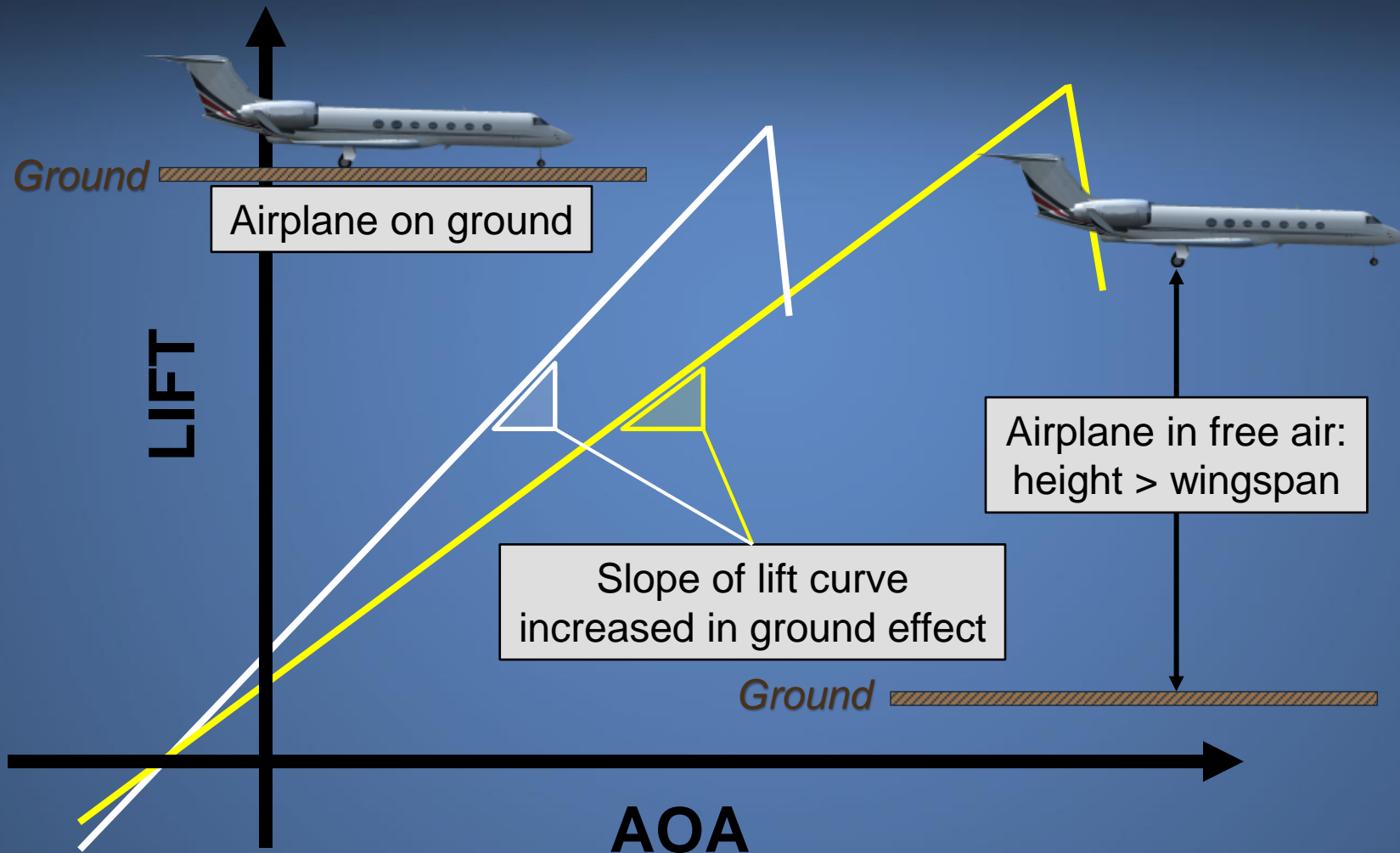
Ground Effect



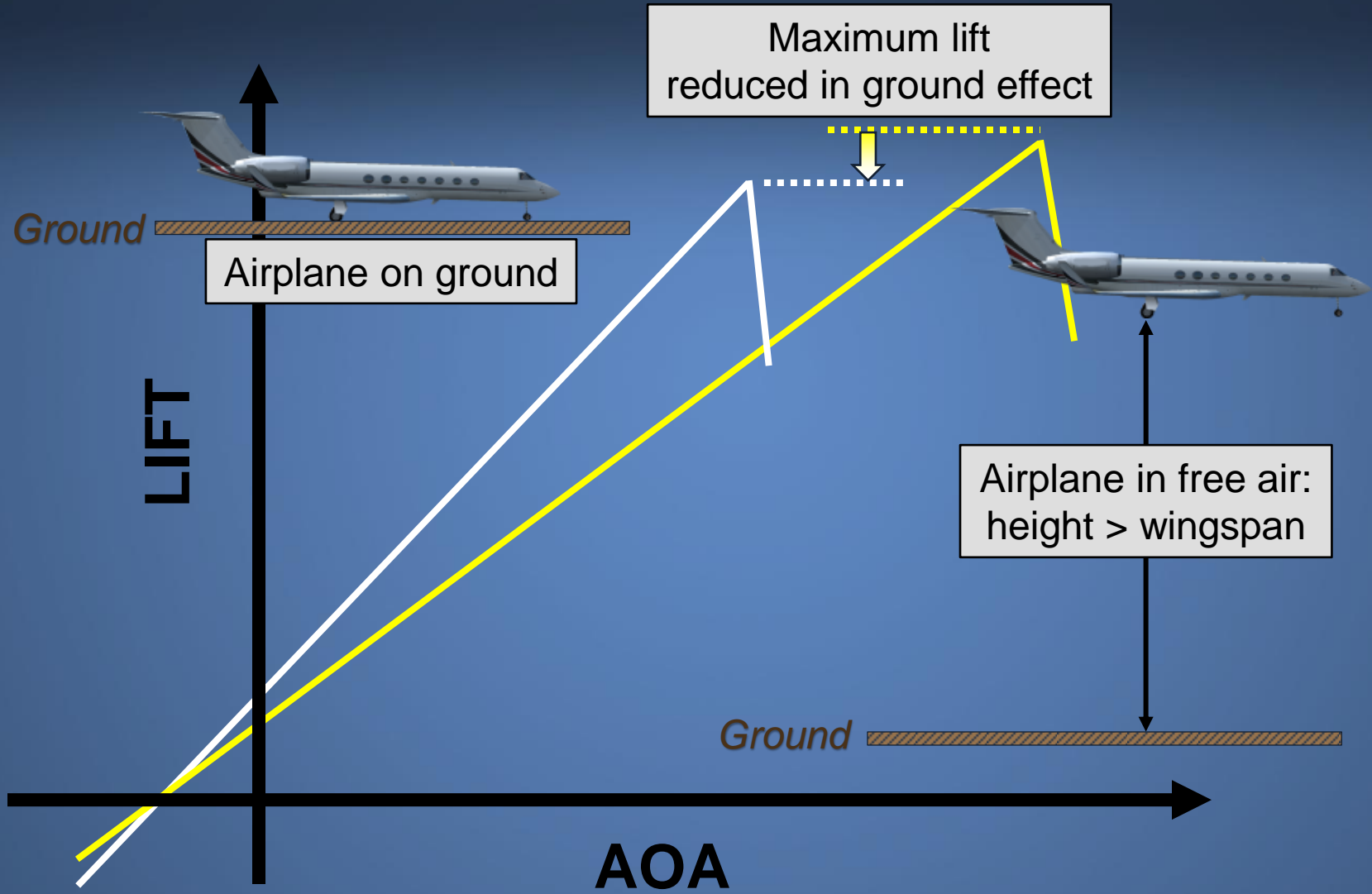
Ground Effect



Ground Effect

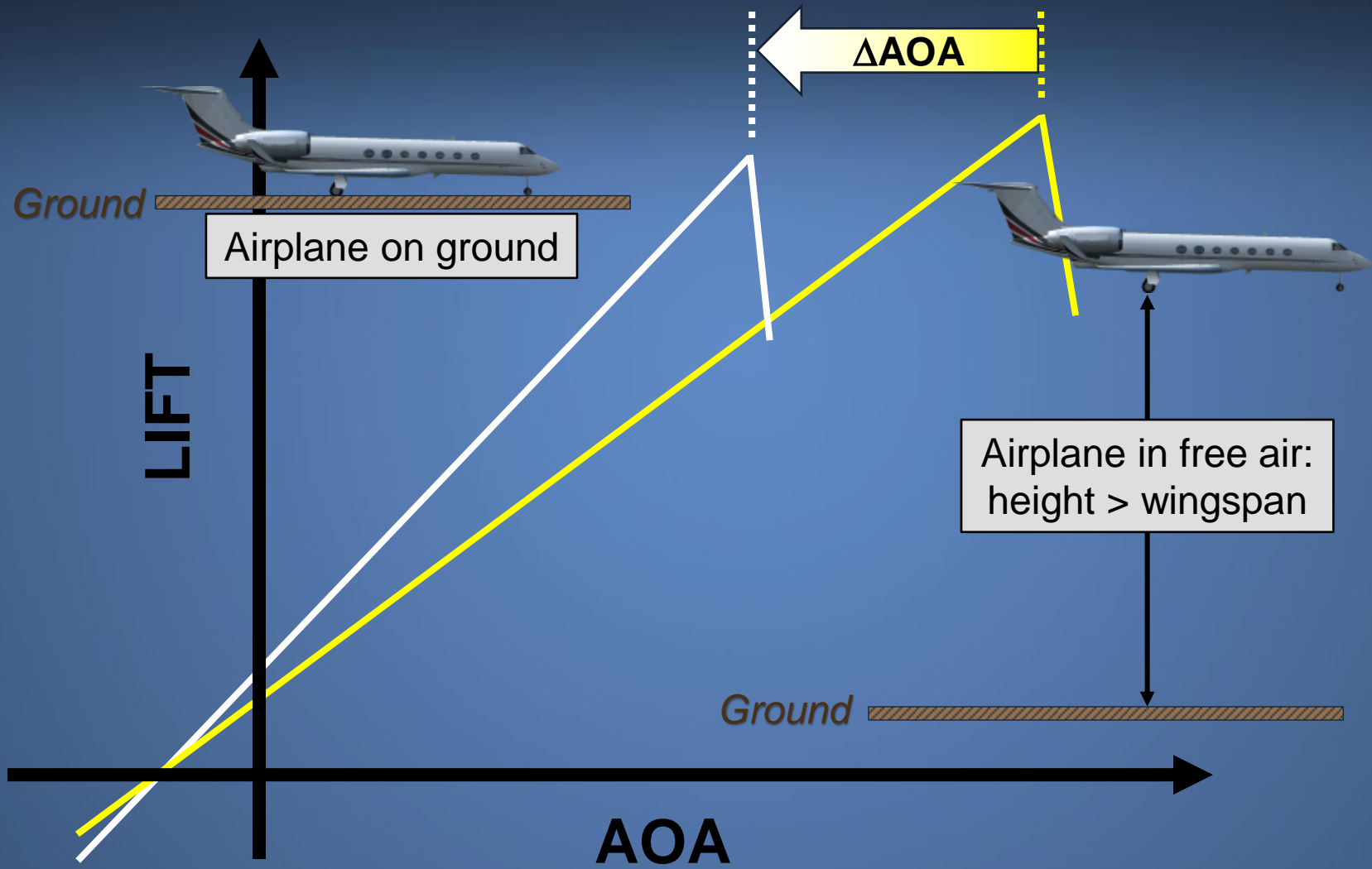


Ground Effect



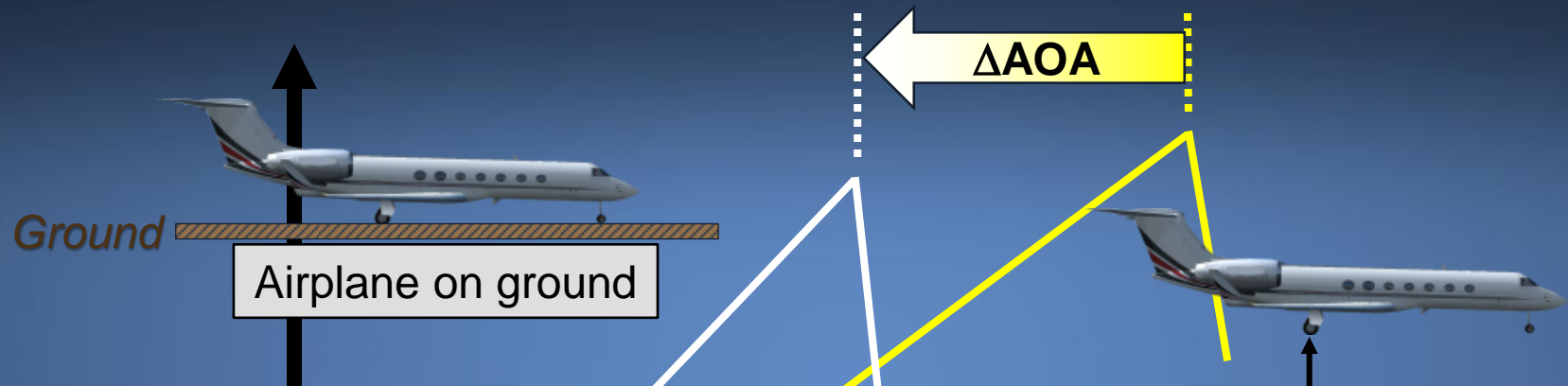
Ground Effect

Stall AOA
reduced in ground effect



Ground Effect

Stall AOA
reduced in ground effect



Estimated ΔAOA (from V_{MU} tests)	Actual ΔAOA (from postaccident CFD)	Difference
1.6°	3.25°	1.65°

RESULT: No warning before stall in ground effect

Missed opportunity: Actual ΔAOA indicated by two previous roll events

AOA

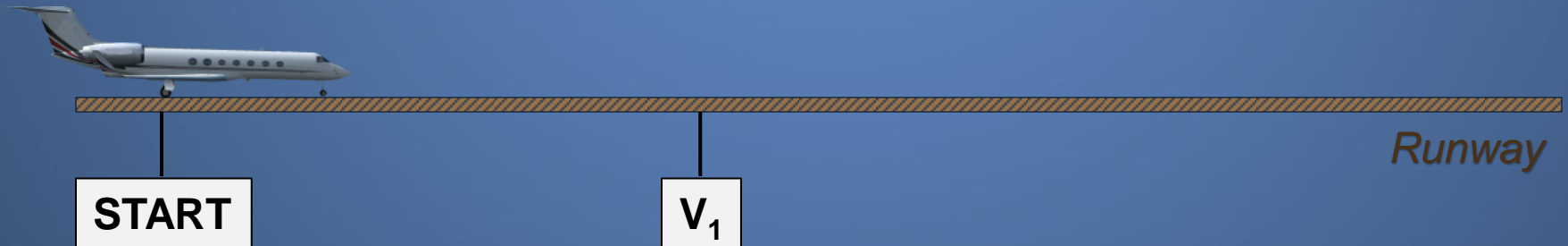
Takeoff Speeds

- Takeoff roll starts with airplane at rest



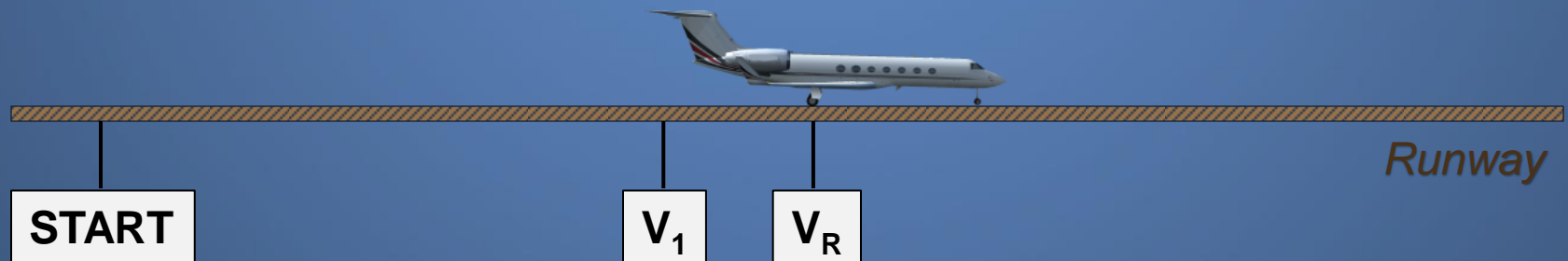
Takeoff Speeds

- Takeoff roll starts with airplane at rest
- Decision speed (V_1): With a failed engine, distance to climb to 35 feet same as distance to stop



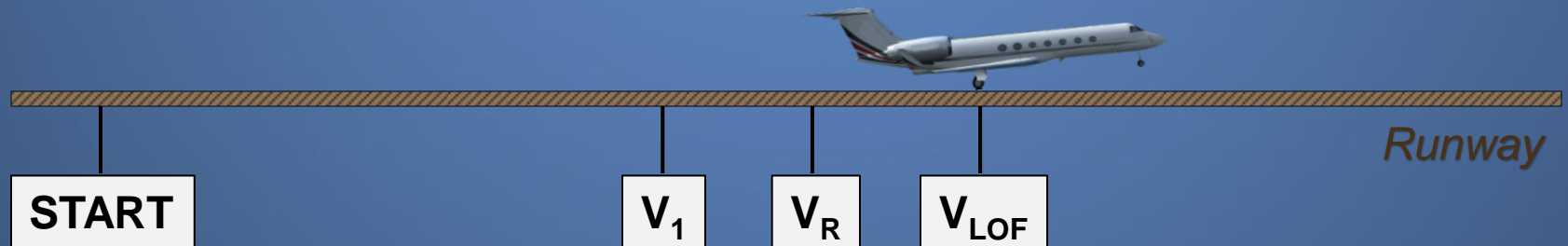
Takeoff Speeds

- Rotation speed (V_R): pilot pulls column to raise the nose for takeoff



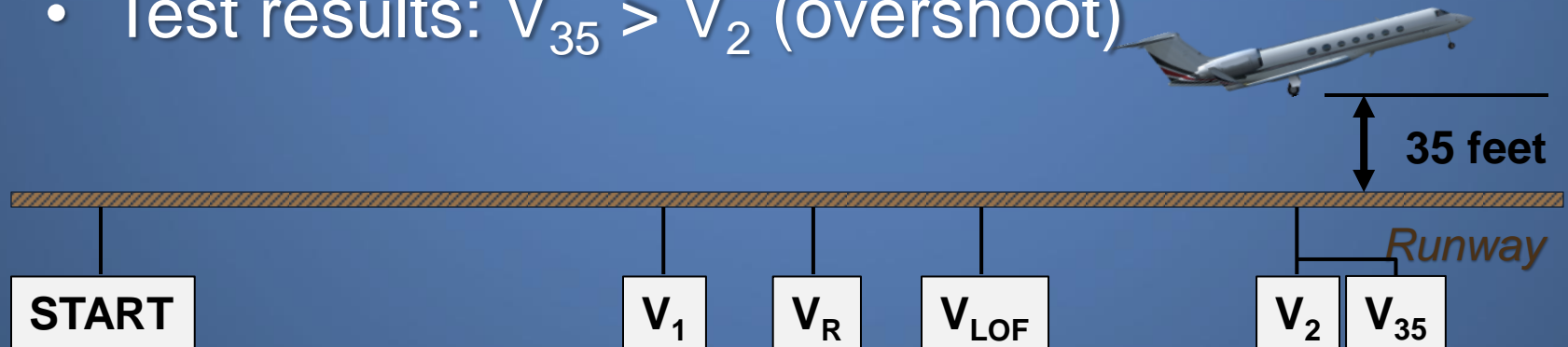
Takeoff Speeds

- Liftoff speed (V_{LOF}): main gear leaves runway



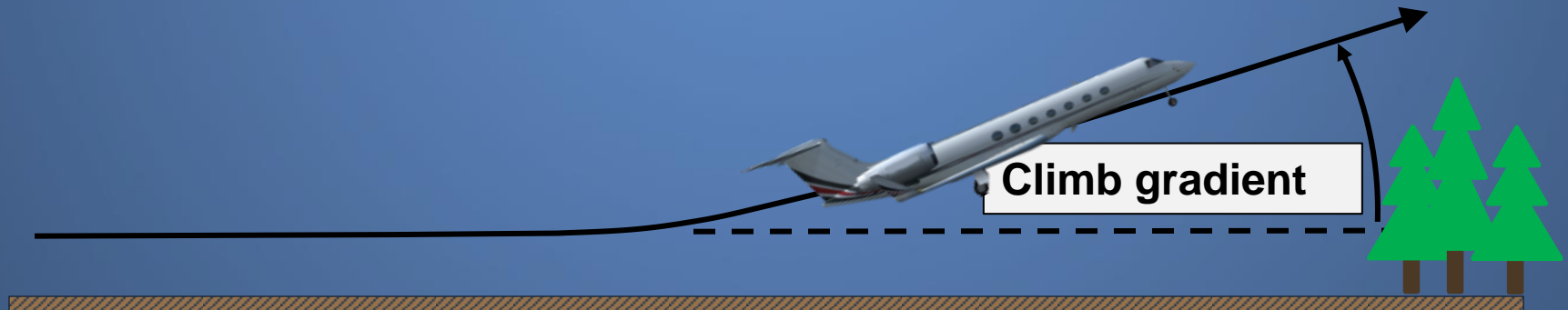
Takeoff Speeds

- Takeoff safety speed (V_2): target climb speed with a failed engine, to be achieved by 35 feet above ground level (agl)
- V_{35} : actual speed at 35 feet agl
- Test objective: $V_{35} = V_2$
- Test results: $V_{35} > V_2$ (overshoot)

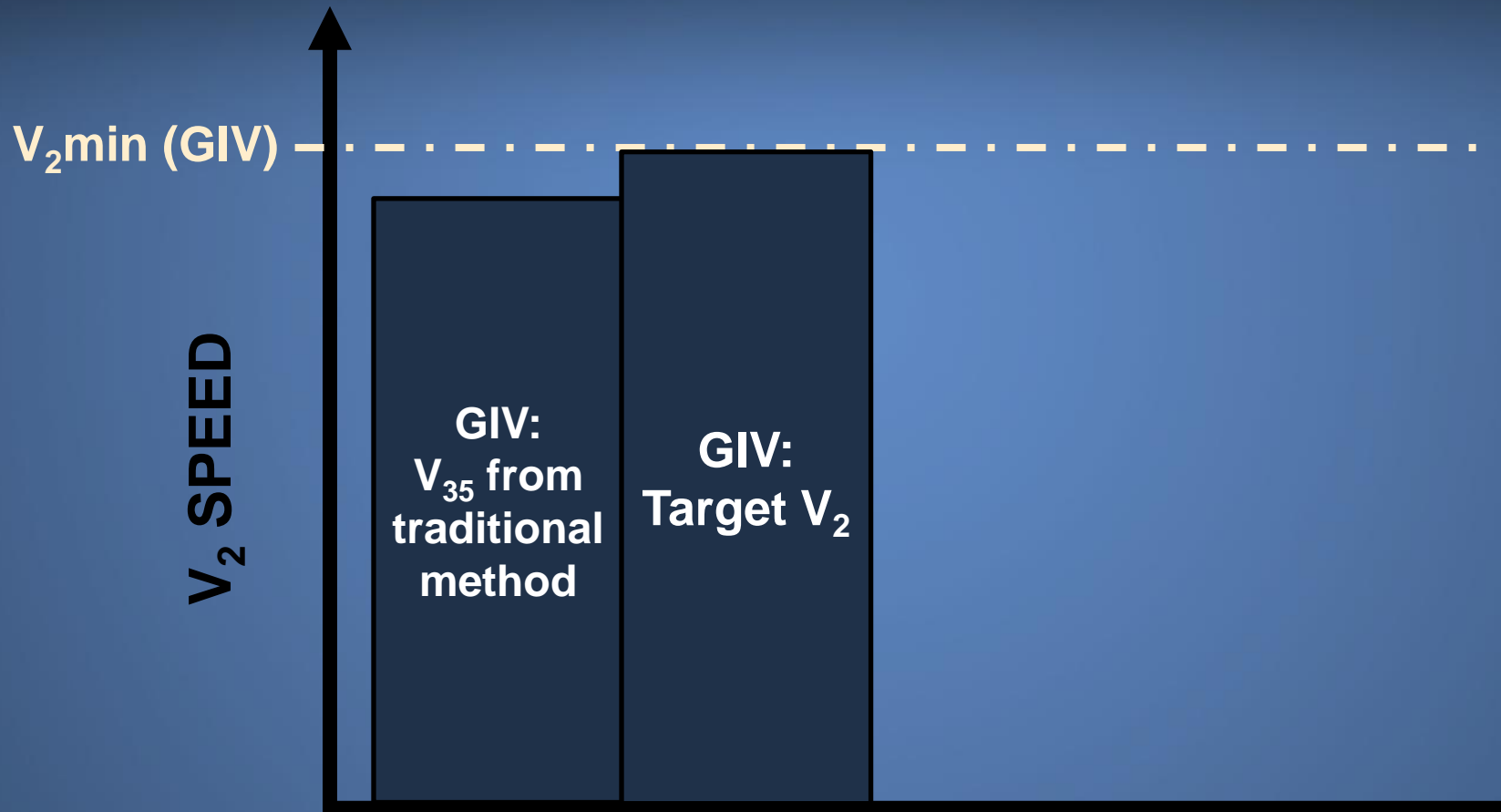


Takeoff Safety Speed (V_2)

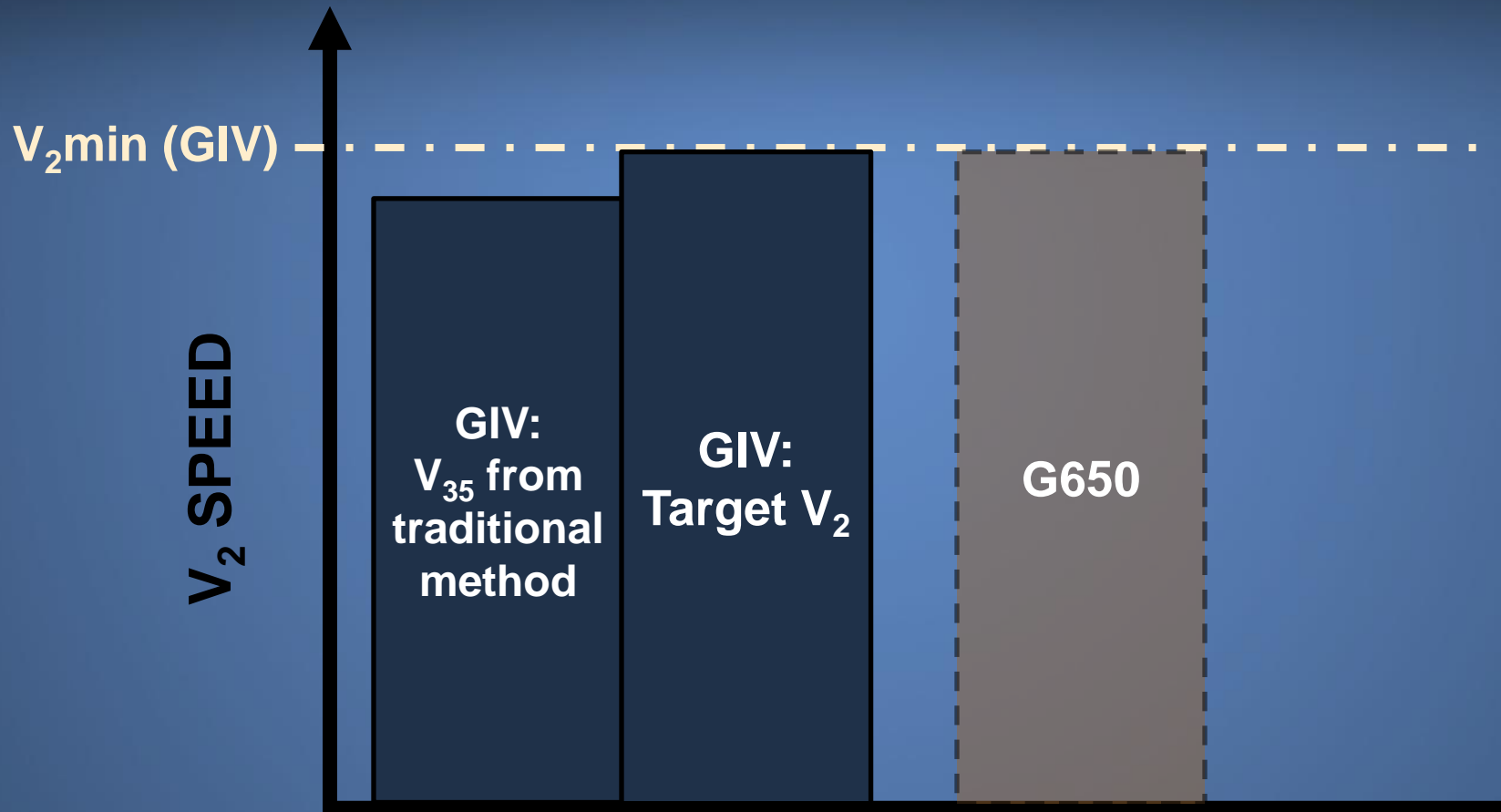
- V_2 requirements intended to ensure
 - Safe AOA margin from stall
 - Safe control of asymmetric thrust with one engine inoperative
 - Safe minimum climb gradient with one engine inoperative



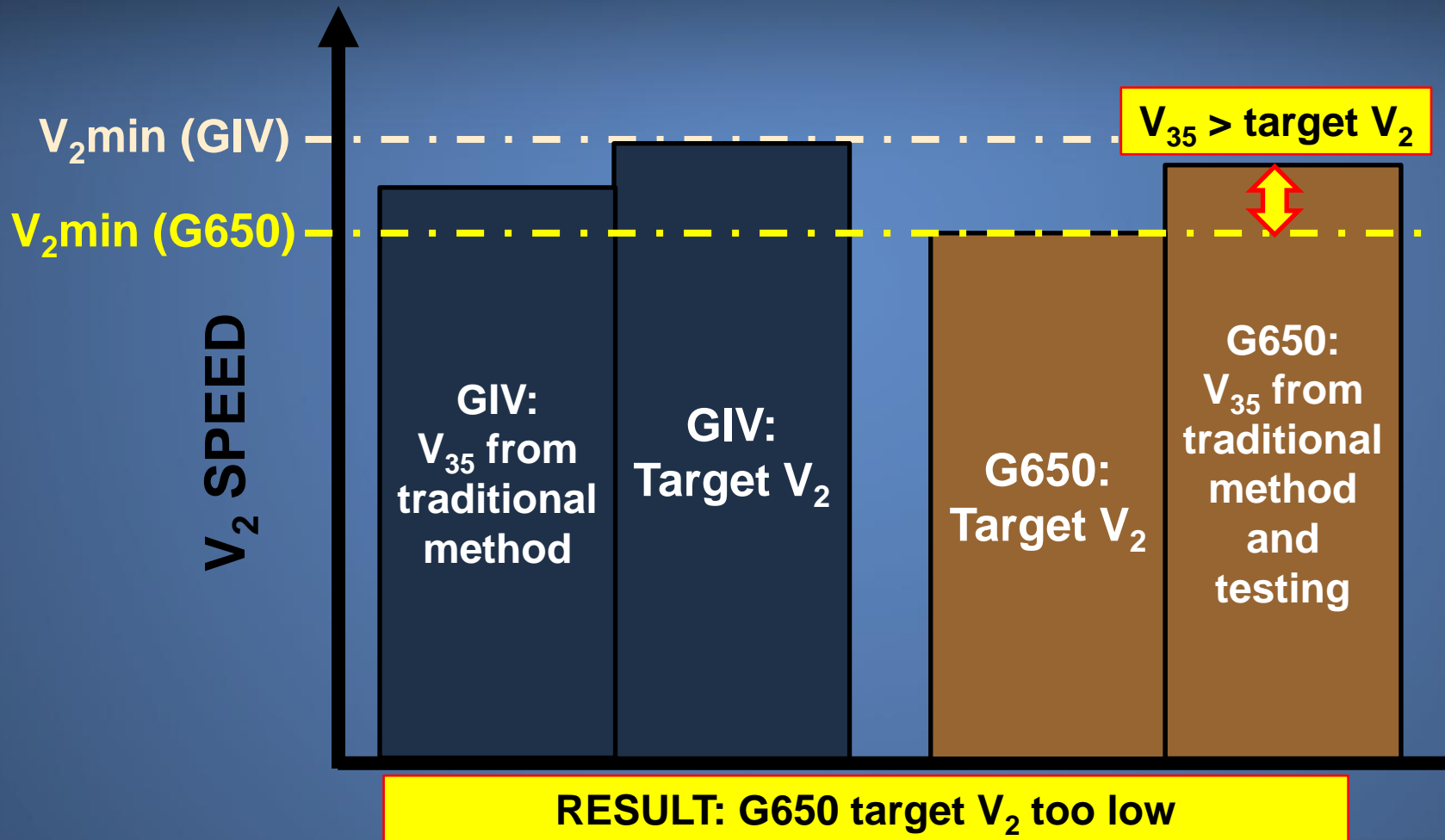
V_2 Development



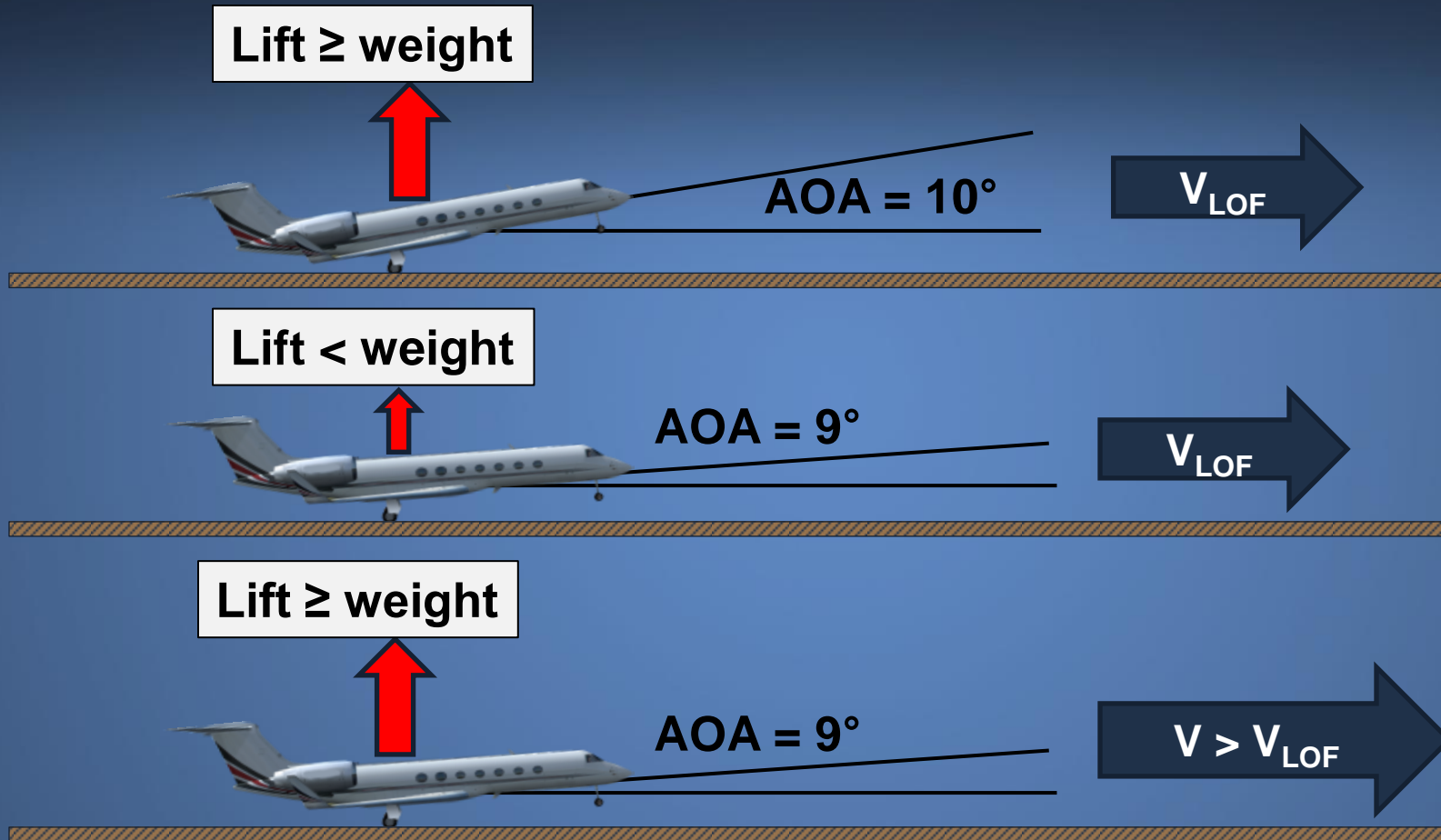
V_2 Development



V₂ Development



Change in Flaps 10 Target Pitch Angle



Reduction in pitch without increase in speed exacerbated V_2 overshoots

V_2 and Takeoff Distance

- Takeoff distance increases with higher V_2
- Achieving target V_2 necessary to satisfy takeoff distance guarantee
- No analysis of physics of G650 rotation to validate speeds or determine root cause of overshoots

Takeoff Rotation Techniques

- Gulfstream attempted to solve V_2 overshoot problem through takeoff rotation technique
- Pitch attitude for climb at V_2 greater than target pitch for takeoff rotation
- V_{35} reduced by reducing time to achieve climb pitch attitude
 - Achieve target pitch sooner (high rotation rate)
 - Increase pitch above target sooner

Takeoff Rotation Techniques: Achieve Target Pitch Sooner

- Abrupt column pull with high force
- V_2 overshoots reduced but not eliminated
- Primary flight test engineer concerned that technique too difficult to be accepted by FAA
- On accident flight, PIC stated technique “doesn’t work”

Takeoff Rotation Techniques: Increase Pitch Above Target Sooner

- Less abrupt column pull with moderate force
- Reduced pauses at target pitch angle
- Increase in pitch to climb attitude became “almost...continuous”
- V_2 overshoots reduced but not eliminated
- Accident takeoff: AOA exceeded stall AOA in ground effect

Summary

- Erroneously low target V_2 speeds resulted in overshoots
- Reduction of pitch target without increase in target speeds exacerbated V_2 overshoots
- V_2 overshoots threatened takeoff distance guarantee
- Pitch angle and AOA increased sooner in successive takeoffs to reduce V_2 overshoots

Summary

- Accident takeoff: AOA exceeded stall AOA in ground effect
- Asymmetrical stall resulted in uncontrollable rolling moment
- Estimate of stall AOA in ground effect too high
 - No stick shaker before stall
 - Actual stall AOA could have been determined from previous events



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